

## PDF hosted at the Radboud Repository of the Radboud University Nijmegen

The following full text is a postprint version which may differ from the publisher's version.

For additional information about this publication click this link.

<http://hdl.handle.net/2066/72709>

Please be advised that this information was generated on 2018-07-08 and may be subject to change.

# Observation of $ZZ$ production in $p\bar{p}$ collisions at $\sqrt{s}=1.96$ TeV

V.M. Abazov<sup>36</sup>, B. Abbott<sup>75</sup>, M. Abolins<sup>65</sup>, B.S. Acharya<sup>29</sup>, M. Adams<sup>51</sup>, T. Adams<sup>49</sup>, E. Aguilo<sup>6</sup>, M. Ahsan<sup>59</sup>, G.D. Alexeev<sup>36</sup>, G. Alkhazov<sup>40</sup>, A. Alton<sup>64,a</sup>, G. Alverson<sup>63</sup>, G.A. Alves<sup>2</sup>, M. Anastasoae<sup>35</sup>, L.S. Ancu<sup>35</sup>, T. Andeen<sup>53</sup>, B. Andrieu<sup>17</sup>, M.S. Anzels<sup>53</sup>, M. Aoki<sup>50</sup>, Y. Arnoud<sup>14</sup>, M. Arov<sup>60</sup>, M. Arthaud<sup>18</sup>, A. Askew<sup>49</sup>, B. Åsman<sup>41</sup>, A.C.S. Assis Jesus<sup>3</sup>, O. Atramentov<sup>49</sup>, C. Avila<sup>8</sup>, F. Badaud<sup>13</sup>, L. Bagby<sup>50</sup>, B. Baldin<sup>50</sup>, D.V. Bandurin<sup>59</sup>, P. Banerjee<sup>29</sup>, S. Banerjee<sup>29</sup>, E. Barberis<sup>63</sup>, A.-F. Barfuss<sup>15</sup>, P. Bargassa<sup>80</sup>, P. Baringer<sup>58</sup>, J. Barreto<sup>2</sup>, J.F. Bartlett<sup>50</sup>, U. Bassler<sup>18</sup>, D. Bauer<sup>43</sup>, S. Beale<sup>6</sup>, A. Bean<sup>58</sup>, M. Begalli<sup>3</sup>, M. Begel<sup>73</sup>, C. Belanger-Champagne<sup>41</sup>, L. Bellantoni<sup>50</sup>, A. Bellavance<sup>50</sup>, J.A. Benitez<sup>65</sup>, S.B. Beri<sup>27</sup>, G. Bernardi<sup>17</sup>, R. Bernhard<sup>23</sup>, I. Bertram<sup>42</sup>, M. Besançon<sup>18</sup>, R. Beuselinck<sup>43</sup>, V.A. Bezzubov<sup>39</sup>, P.C. Bhat<sup>50</sup>, V. Bhatnagar<sup>27</sup>, C. Biscarat<sup>20</sup>, G. Blazey<sup>52</sup>, F. Blekman<sup>43</sup>, S. Blessing<sup>49</sup>, K. Bloom<sup>67</sup>, A. Boehnlein<sup>50</sup>, D. Boline<sup>62</sup>, T.A. Bolton<sup>59</sup>, E.E. Boos<sup>38</sup>, G. Borissov<sup>42</sup>, T. Bose<sup>77</sup>, A. Brandt<sup>78</sup>, R. Brock<sup>65</sup>, G. Brooijmans<sup>70</sup>, A. Bross<sup>50</sup>, D. Brown<sup>81</sup>, X.B. Bu<sup>7</sup>, N.J. Buchanan<sup>49</sup>, D. Buchholz<sup>53</sup>, M. Buehler<sup>81</sup>, V. Buescher<sup>22</sup>, V. Bunichev<sup>38</sup>, S. Burdin<sup>42,b</sup>, T.H. Burnett<sup>82</sup>, C.P. Buszello<sup>43</sup>, J.M. Butler<sup>62</sup>, P. Calfayan<sup>25</sup>, S. Calvet<sup>16</sup>, J. Cammin<sup>71</sup>, E. Carrera<sup>49</sup>, W. Carvalho<sup>3</sup>, B.C.K. Casey<sup>50</sup>, H. Castilla-Valdez<sup>33</sup>, G. Cerminara<sup>63,c</sup>, S. Chakrabarti<sup>18</sup>, D. Chakraborty<sup>52</sup>, K.M. Chan<sup>55</sup>, A. Chandra<sup>48</sup>, E. Cheu<sup>45</sup>, F. Chevallier<sup>14</sup>, D.K. Cho<sup>62</sup>, S. Choi<sup>32</sup>, B. Choudhary<sup>28</sup>, L. Christofek<sup>77</sup>, T. Christoudias<sup>43</sup>, S. Cihangir<sup>50</sup>, D. Claes<sup>67</sup>, J. Clutter<sup>58</sup>, M. Cooke<sup>50</sup>, W.E. Cooper<sup>50</sup>, M. Corcoran<sup>80</sup>, F. Couderc<sup>18</sup>, M.-C. Cousinou<sup>15</sup>, S. Crépé-Renaudin<sup>14</sup>, V. Cuplov<sup>59</sup>, D. Cutts<sup>77</sup>, M. Cwiok<sup>30</sup>, H. da Motta<sup>2</sup>, A. Das<sup>45</sup>, G. Davies<sup>43</sup>, K. De<sup>78</sup>, S.J. de Jong<sup>35</sup>, E. De La Cruz-Burelo<sup>33</sup>, C. De Oliveira Martins<sup>3</sup>, K. DeVaughan<sup>67</sup>, J.D. Degenhardt<sup>64</sup>, F. Déliot<sup>18</sup>, M. Demarteau<sup>50</sup>, R. Demina<sup>71</sup>, D. Denisov<sup>50</sup>, S.P. Denisov<sup>39</sup>, S. Desai<sup>50</sup>, H.T. Diehl<sup>50</sup>, M. Diesburg<sup>50</sup>, A. Dominguez<sup>67</sup>, H. Dong<sup>72</sup>, T. Dorland<sup>82</sup>, A. Dubey<sup>28</sup>, L.V. Dudko<sup>38</sup>, L. Duflot<sup>16</sup>, S.R. Dugad<sup>29</sup>, D. Duggan<sup>49</sup>, A. Duperrin<sup>15</sup>, J. Dyer<sup>65</sup>, A. Dyshkant<sup>52</sup>, M. Eads<sup>67</sup>, D. Edmunds<sup>65</sup>, J. Ellison<sup>48</sup>, V.D. Elvira<sup>50</sup>, Y. Enari<sup>77</sup>, S. Eno<sup>61</sup>, P. Ermolov<sup>38,†</sup>, H. Evans<sup>54</sup>, A. Evdokimov<sup>73</sup>, V.N. Evdokimov<sup>39</sup>, G. Facini<sup>63</sup>, A.V. Ferapontov<sup>59</sup>, T. Ferbel<sup>71</sup>, F. Fiedler<sup>24</sup>, F. Filthaut<sup>35</sup>, W. Fisher<sup>50</sup>, H.E. Fisk<sup>50</sup>, M. Fortner<sup>52</sup>, H. Fox<sup>42</sup>, S. Fu<sup>50</sup>, S. Fuess<sup>50</sup>, T. Gadfort<sup>70</sup>, C.F. Galea<sup>35</sup>, C. Garcia<sup>71</sup>, A. Garcia-Bellido<sup>71</sup>, V. Gavrilov<sup>37</sup>, P. Gay<sup>13</sup>, W. Geist<sup>19</sup>, W. Geng<sup>15,65</sup>, C.E. Gerber<sup>51</sup>, Y. Gershtein<sup>49</sup>, D. Gillberg<sup>6</sup>, G. Ginther<sup>71</sup>, N. Gollub<sup>41</sup>, B. Gómez<sup>8</sup>, A. Goussiou<sup>82</sup>, P.D. Grannis<sup>72</sup>, H. Greenlee<sup>50</sup>, Z.D. Greenwood<sup>60</sup>, E.M. Gregores<sup>4</sup>, G. Grenier<sup>20</sup>, Ph. Gris<sup>13</sup>, J.-F. Grivaz<sup>16</sup>, A. Grohsjean<sup>25</sup>, S. Grünendahl<sup>50</sup>, M.W. Grünewald<sup>30</sup>, F. Guo<sup>72</sup>, J. Guo<sup>72</sup>, G. Gutierrez<sup>50</sup>, P. Gutierrez<sup>75</sup>, A. Haas<sup>70</sup>, N.J. Hadley<sup>61</sup>, P. Haefner<sup>25</sup>, S. Hagopian<sup>49</sup>, J. Haley<sup>68</sup>, I. Hall<sup>65</sup>, R.E. Hall<sup>47</sup>, L. Han<sup>7</sup>, K. Harder<sup>44</sup>, A. Harel<sup>71</sup>, J.M. Hauptman<sup>57</sup>, J. Hays<sup>43</sup>, T. Hebbeker<sup>21</sup>, D. Hedin<sup>52</sup>, J.G. Hegeman<sup>34</sup>, A.P. Heinson<sup>48</sup>, U. Heintz<sup>62</sup>, C. Hensel<sup>22,d</sup>, K. Herner<sup>72</sup>, G. Hesketh<sup>63</sup>, M.D. Hildreth<sup>55</sup>, R. Hirosky<sup>81</sup>, J.D. Hobbs<sup>72</sup>, B. Hoeneisen<sup>12</sup>, H. Hoeth<sup>26</sup>, M. Hohlfield<sup>22</sup>, S. Hossain<sup>75</sup>, P. Houben<sup>34</sup>, Y. Hu<sup>72</sup>, Z. Hubacek<sup>10</sup>, V. Hynek<sup>9</sup>, I. Iashvili<sup>69</sup>, R. Illingworth<sup>50</sup>, A.S. Ito<sup>50</sup>, S. Jabeen<sup>62</sup>, M. Jaffré<sup>16</sup>, S. Jain<sup>75</sup>, K. Jakobs<sup>23</sup>, C. Jarvis<sup>61</sup>, R. Jesik<sup>43</sup>, K. Johns<sup>45</sup>, C. Johnson<sup>70</sup>, M. Johnson<sup>50</sup>, D. Johnston<sup>67</sup>, A. Jonckheere<sup>50</sup>, P. Jonsson<sup>43</sup>, A. Juste<sup>50</sup>, E. Kajfasz<sup>15</sup>, J.M. Kalk<sup>60</sup>, D. Karmanov<sup>38</sup>, P.A. Kasper<sup>50</sup>, I. Katsanos<sup>70</sup>, D. Kau<sup>49</sup>, V. Kaushik<sup>78</sup>, R. Kehoe<sup>79</sup>, S. Kermiche<sup>15</sup>, N. Khalatyan<sup>50</sup>, A. Khanov<sup>76</sup>, A. Kharchilava<sup>69</sup>, Y.M. Kharzheev<sup>36</sup>, D. Khatidze<sup>70</sup>, T.J. Kim<sup>31</sup>, M.H. Kirby<sup>53</sup>, M. Kirsch<sup>21</sup>, B. Klima<sup>50</sup>, J.M. Kohli<sup>27</sup>, J.-P. Konrath<sup>23</sup>, A.V. Kozelov<sup>39</sup>, J. Kraus<sup>65</sup>, T. Kuhl<sup>24</sup>, A. Kumar<sup>69</sup>, A. Kupco<sup>11</sup>, T. Kurča<sup>20</sup>, V.A. Kuzmin<sup>38</sup>, J. Kvita<sup>9</sup>, F. Lacroix<sup>13</sup>, D. Lam<sup>55</sup>, S. Lammers<sup>70</sup>, G. Landsberg<sup>77</sup>, P. Lebrun<sup>20</sup>, W.M. Lee<sup>50</sup>, A. Leflat<sup>38</sup>, J. Lellouch<sup>17</sup>, J. Li<sup>78,‡</sup>, L. Li<sup>48</sup>, Q.Z. Li<sup>50</sup>, S.M. Lietti<sup>5</sup>, J.K. Lim<sup>31</sup>, J.G.R. Lima<sup>52</sup>, D. Lincoln<sup>50</sup>, J. Linnemann<sup>65</sup>, V.V. Lipaev<sup>39</sup>, R. Lipton<sup>50</sup>, Y. Liu<sup>7</sup>, Z. Liu<sup>6</sup>, A. Lobodenko<sup>40</sup>, M. Lokajicek<sup>11</sup>, P. Love<sup>42</sup>, H.J. Lubatti<sup>82</sup>, R. Luna<sup>3</sup>, A.L. Lyon<sup>50</sup>, A.K.A. Maciel<sup>2</sup>, D. Mackin<sup>80</sup>, R.J. Madaras<sup>46</sup>, P. Mättig<sup>26</sup>, C. Magass<sup>21</sup>, A. Magerkurth<sup>64</sup>, P.K. Mal<sup>82</sup>, H.B. Malbouisson<sup>3</sup>, S. Malik<sup>67</sup>, V.L. Malyshev<sup>36</sup>, Y. Maravin<sup>59</sup>, B. Martin<sup>14</sup>, R. McCarthy<sup>72</sup>, A. Melnitchouk<sup>66</sup>, L. Mendoza<sup>8</sup>, P.G. Mercadante<sup>5</sup>, M. Merkin<sup>38</sup>, K.W. Merritt<sup>50</sup>, A. Meyer<sup>21</sup>, J. Meyer<sup>22,d</sup>, J. Mitrevski<sup>70</sup>, R.K. Mommsen<sup>44</sup>, N.K. Mondal<sup>29</sup>, R.W. Moore<sup>6</sup>, T. Moulik<sup>58</sup>, G.S. Muanza<sup>20</sup>, M. Mulhearn<sup>70</sup>, O. Mundal<sup>22</sup>, L. Mundim<sup>3</sup>, E. Nagy<sup>15</sup>, M. Naimuddin<sup>50</sup>, M. Narain<sup>77</sup>, N.A. Naumann<sup>35</sup>, H.A. Neal<sup>64</sup>, J.P. Negret<sup>8</sup>, P. Neustroev<sup>40</sup>, H. Nilsen<sup>23</sup>, H. Nogima<sup>3</sup>, S.F. Novaes<sup>5</sup>, T. Nunnemann<sup>25</sup>, V. O'Dell<sup>50</sup>, D.C. O'Neil<sup>6</sup>, G. Obrant<sup>40</sup>, C. Ochando<sup>16</sup>, D. Onoprienko<sup>59</sup>, N. Oshima<sup>50</sup>, N. Osman<sup>43</sup>, J. Osta<sup>55</sup>, R. Otec<sup>10</sup>, G.J. Otero y Garzón<sup>50</sup>, M. Owen<sup>44</sup>, P. Padley<sup>80</sup>, M. Pangilinan<sup>77</sup>, N. Parashar<sup>56</sup>, S.-J. Park<sup>22,d</sup>, S.K. Park<sup>31</sup>, J. Parsons<sup>70</sup>, R. Partridge<sup>77</sup>, N. Parua<sup>54</sup>, A. Patwa<sup>73</sup>, G. Pawloski<sup>80</sup>, B. Penning<sup>23</sup>, M. Perfilov<sup>38</sup>, K. Peters<sup>44</sup>, Y. Peters<sup>26</sup>, P. Pétrouff<sup>16</sup>, M. Petteni<sup>43</sup>, R. Piegaia<sup>1</sup>, J. Piper<sup>65</sup>,

M.-A. Pleier<sup>22</sup>, P.L.M. Podesta-Lerma<sup>33,d</sup>, V.M. Podstavkov<sup>50</sup>, Y. Pogorelov<sup>55</sup>, M.-E. Pol<sup>2</sup>, P. Polozov<sup>37</sup>, B.G. Pope<sup>65</sup>, A.V. Popov<sup>39</sup>, C. Potter<sup>6</sup>, W.L. Prado da Silva<sup>3</sup>, H.B. Prosper<sup>49</sup>, S. Protopopescu<sup>73</sup>, J. Qian<sup>64</sup>, A. Quadt<sup>22,e</sup>, B. Quinn<sup>66</sup>, A. Rakitine<sup>42</sup>, M.S. Rangel<sup>2</sup>, K. Ranjan<sup>28</sup>, P.N. Ratoff<sup>42</sup>, I. Razumov<sup>39</sup>, P. Renkel<sup>79</sup>, P. Rich<sup>44</sup>, J. Rieger<sup>54</sup>, M. Rijssenbeek<sup>72</sup>, I. Ripp-Baudot<sup>19</sup>, F. Rizatdinova<sup>76</sup>, S. Robinson<sup>43</sup>, R.F. Rodrigues<sup>3</sup>, M. Rominsky<sup>75</sup>, C. Royon<sup>18</sup>, P. Rubinov<sup>50</sup>, R. Ruchti<sup>55</sup>, G. Safronov<sup>37</sup>, G. Sajot<sup>14</sup>, A. Sánchez-Hernández<sup>33</sup>, M.P. Sanders<sup>17</sup>, B. Sanghi<sup>50</sup>, G. Savage<sup>50</sup>, L. Sawyer<sup>60</sup>, T. Scanlon<sup>43</sup>, D. Schaile<sup>25</sup>, R.D. Schamberger<sup>72</sup>, Y. Scheglov<sup>40</sup>, H. Schellman<sup>53</sup>, T. Schliephake<sup>26</sup>, S. Schlobohm<sup>82</sup>, C. Schwanenberger<sup>44</sup>, A. Schwartzman<sup>68</sup>, R. Schwienhorst<sup>65</sup>, J. Sekaric<sup>49</sup>, H. Severini<sup>75</sup>, E. Shabalina<sup>51</sup>, M. Shamim<sup>59</sup>, V. Shary<sup>18</sup>, A.A. Shchukin<sup>39</sup>, R.K. Shivpuri<sup>28</sup>, V. Siccaldi<sup>19</sup>, V. Simak<sup>10</sup>, V. Sirotenko<sup>50</sup>, P. Skubic<sup>75</sup>, P. Slattery<sup>71</sup>, D. Smirnov<sup>55</sup>, G.R. Snow<sup>67</sup>, J. Snow<sup>74</sup>, S. Snyder<sup>73</sup>, S. Söldner-Rembold<sup>44</sup>, L. Sonnenschein<sup>17</sup>, A. Sopczak<sup>42</sup>, M. Sosebee<sup>78</sup>, K. Soustruznik<sup>9</sup>, B. Spurlock<sup>78</sup>, J. Stark<sup>14</sup>, J. Steele<sup>60</sup>, V. Stolin<sup>37</sup>, D.A. Stoyanova<sup>39</sup>, J. Strandberg<sup>64</sup>, S. Strandberg<sup>41</sup>, M.A. Strang<sup>69</sup>, E. Strauss<sup>72</sup>, M. Strauss<sup>75</sup>, R. Ströhmer<sup>25</sup>, D. Strom<sup>53</sup>, L. Stutte<sup>50</sup>, S. Sumowidagdo<sup>49</sup>, P. Svoisky<sup>55</sup>, A. Sznajder<sup>3</sup>, P. Tamburello<sup>45</sup>, A. Tanasijczuk<sup>1</sup>, W. Taylor<sup>6</sup>, B. Tiller<sup>25</sup>, F. Tissandier<sup>13</sup>, M. Titov<sup>18</sup>, V.V. Tokmenin<sup>36</sup>, I. Torchiani<sup>23</sup>, D. Tsybychev<sup>72</sup>, B. Tuchming<sup>18</sup>, C. Tully<sup>68</sup>, P.M. Tuts<sup>70</sup>, R. Unalan<sup>65</sup>, L. Uvarov<sup>40</sup>, S. Uvarov<sup>40</sup>, S. Uzunyan<sup>52</sup>, B. Vachon<sup>6</sup>, P.J. van den Berg<sup>34</sup>, R. Van Kooten<sup>54</sup>, W.M. van Leeuwen<sup>34</sup>, N. Varelas<sup>51</sup>, E.W. Varnes<sup>45</sup>, I.A. Vasilyev<sup>39</sup>, P. Verdier<sup>20</sup>, L.S. Vertogradov<sup>36</sup>, M. Verzocchi<sup>50</sup>, D. Vilanova<sup>18</sup>, F. Villeneuve-Segui<sup>43</sup>, P. Vint<sup>43</sup>, P. Vokac<sup>10</sup>, M. Voutilainen<sup>67,f</sup>, R. Wagner<sup>68</sup>, H.D. Wahl<sup>49</sup>, M.H.L.S. Wang<sup>50</sup>, J. Warchol<sup>55</sup>, G. Watts<sup>82</sup>, M. Wayne<sup>55</sup>, G. Weber<sup>24</sup>, M. Weber<sup>50,g</sup>, L. Welty-Rieger<sup>54</sup>, A. Wenger<sup>23,h</sup>, N. Wermes<sup>22</sup>, M. Wetstein<sup>61</sup>, A. White<sup>78</sup>, D. Wicke<sup>26</sup>, M. Williams<sup>42</sup>, G.W. Wilson<sup>58</sup>, S.J. Wimpenny<sup>48</sup>, M. Wobisch<sup>60</sup>, D.R. Wood<sup>63</sup>, T.R. Wyatt<sup>44</sup>, Y. Xie<sup>77</sup>, S. Yacooob<sup>53</sup>, R. Yamada<sup>50</sup>, W.-C. Yang<sup>44</sup>, T. Yasuda<sup>50</sup>, Y.A. Yatsunenko<sup>36</sup>, H. Yin<sup>7</sup>, K. Yip<sup>73</sup>, H.D. Yoo<sup>77</sup>, S.W. Youn<sup>53</sup>, J. Yu<sup>78</sup>, C. Zeitnitz<sup>26</sup>, S. Zelitch<sup>81</sup>, T. Zhao<sup>82</sup>, B. Zhou<sup>64</sup>, J. Zhu<sup>72</sup>, M. Zielinski<sup>71</sup>, D. Zieminska<sup>54</sup>, A. Zieminski<sup>54,†</sup>, L. Zivkovic<sup>70</sup>, V. Zutshi<sup>52</sup>, and E.G. Zverev<sup>38</sup>

(The DØ Collaboration)

<sup>1</sup>Universidad de Buenos Aires, Buenos Aires, Argentina

<sup>2</sup>LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

<sup>3</sup>Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

<sup>4</sup>Universidade Federal do ABC, Santo André, Brazil

<sup>5</sup>Instituto de Física Teórica, Universidade Estadual Paulista, São Paulo, Brazil

<sup>6</sup>University of Alberta, Edmonton, Alberta, Canada,

Simon Fraser University, Burnaby, British Columbia,

Canada, York University, Toronto, Ontario, Canada,

and McGill University, Montreal, Quebec, Canada

<sup>7</sup>University of Science and Technology of China, Hefei, People's Republic of China

<sup>8</sup>Universidad de los Andes, Bogotá, Colombia

<sup>9</sup>Center for Particle Physics, Charles University, Prague, Czech Republic

<sup>10</sup>Czech Technical University, Prague, Czech Republic

<sup>11</sup>Center for Particle Physics, Institute of Physics,  
Academy of Sciences of the Czech Republic, Prague, Czech Republic

<sup>12</sup>Universidad San Francisco de Quito, Quito, Ecuador

<sup>13</sup>LPC, Université Blaise Pascal, CNRS/IN2P3, Clermont, France

<sup>14</sup>LPSC, Université Joseph Fourier Grenoble 1, CNRS/IN2P3,

Institut National Polytechnique de Grenoble, Grenoble, France

<sup>15</sup>CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France

<sup>16</sup>LAL, Université Paris-Sud, IN2P3/CNRS, Orsay, France

<sup>17</sup>LPNHE, IN2P3/CNRS, Universités Paris VI and VII, Paris, France

<sup>18</sup>CEA, Irfu, SPP, Saclay, France

<sup>19</sup>IPHC, Université Louis Pasteur, CNRS/IN2P3, Strasbourg, France

<sup>20</sup>IPNL, Université Lyon 1, CNRS/IN2P3, Villeurbanne, France and Université de Lyon, Lyon, France

<sup>21</sup>III. Physikalisches Institut A, RWTH Aachen University, Aachen, Germany

<sup>22</sup>Physikalisches Institut, Universität Bonn, Bonn, Germany

<sup>23</sup>Physikalisches Institut, Universität Freiburg, Freiburg, Germany

<sup>24</sup>Institut für Physik, Universität Mainz, Mainz, Germany

<sup>25</sup>Ludwig-Maximilians-Universität München, München, Germany

<sup>26</sup>Fachbereich Physik, University of Wuppertal, Wuppertal, Germany

<sup>27</sup>Panjab University, Chandigarh, India

<sup>28</sup>Delhi University, Delhi, India

<sup>29</sup>Tata Institute of Fundamental Research, Mumbai, India

- <sup>30</sup> *University College Dublin, Dublin, Ireland*  
<sup>31</sup> *Korea Detector Laboratory, Korea University, Seoul, Korea*  
<sup>32</sup> *SungKyunKwan University, Suwon, Korea*  
<sup>33</sup> *CINVESTAV, Mexico City, Mexico*  
<sup>34</sup> *FOM-Institute NIKHEF and University of Amsterdam/NIKHEF, Amsterdam, The Netherlands*  
<sup>35</sup> *Radboud University Nijmegen/NIKHEF, Nijmegen, The Netherlands*  
<sup>36</sup> *Joint Institute for Nuclear Research, Dubna, Russia*  
<sup>37</sup> *Institute for Theoretical and Experimental Physics, Moscow, Russia*  
<sup>38</sup> *Moscow State University, Moscow, Russia*  
<sup>39</sup> *Institute for High Energy Physics, Protvino, Russia*  
<sup>40</sup> *Petersburg Nuclear Physics Institute, St. Petersburg, Russia*  
<sup>41</sup> *Lund University, Lund, Sweden, Royal Institute of Technology and Stockholm University, Stockholm, Sweden, and Uppsala University, Uppsala, Sweden*  
<sup>42</sup> *Lancaster University, Lancaster, United Kingdom*  
<sup>43</sup> *Imperial College, London, United Kingdom*  
<sup>44</sup> *University of Manchester, Manchester, United Kingdom*  
<sup>45</sup> *University of Arizona, Tucson, Arizona 85721, USA*  
<sup>46</sup> *Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA*  
<sup>47</sup> *California State University, Fresno, California 93740, USA*  
<sup>48</sup> *University of California, Riverside, California 92521, USA*  
<sup>49</sup> *Florida State University, Tallahassee, Florida 32306, USA*  
<sup>50</sup> *Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*  
<sup>51</sup> *University of Illinois at Chicago, Chicago, Illinois 60607, USA*  
<sup>52</sup> *Northern Illinois University, DeKalb, Illinois 60115, USA*  
<sup>53</sup> *Northwestern University, Evanston, Illinois 60208, USA*  
<sup>54</sup> *Indiana University, Bloomington, Indiana 47405, USA*  
<sup>55</sup> *University of Notre Dame, Notre Dame, Indiana 46556, USA*  
<sup>56</sup> *Purdue University Calumet, Hammond, Indiana 46323, USA*  
<sup>57</sup> *Iowa State University, Ames, Iowa 50011, USA*  
<sup>58</sup> *University of Kansas, Lawrence, Kansas 66045, USA*  
<sup>59</sup> *Kansas State University, Manhattan, Kansas 66506, USA*  
<sup>60</sup> *Louisiana Tech University, Ruston, Louisiana 71272, USA*  
<sup>61</sup> *University of Maryland, College Park, Maryland 20742, USA*  
<sup>62</sup> *Boston University, Boston, Massachusetts 02215, USA*  
<sup>63</sup> *Northeastern University, Boston, Massachusetts 02115, USA*  
<sup>64</sup> *University of Michigan, Ann Arbor, Michigan 48109, USA*  
<sup>65</sup> *Michigan State University, East Lansing, Michigan 48824, USA*  
<sup>66</sup> *University of Mississippi, University, Mississippi 38677, USA*  
<sup>67</sup> *University of Nebraska, Lincoln, Nebraska 68588, USA*  
<sup>68</sup> *Princeton University, Princeton, New Jersey 08544, USA*  
<sup>69</sup> *State University of New York, Buffalo, New York 14260, USA*  
<sup>70</sup> *Columbia University, New York, New York 10027, USA*  
<sup>71</sup> *University of Rochester, Rochester, New York 14627, USA*  
<sup>72</sup> *State University of New York, Stony Brook, New York 11794, USA*  
<sup>73</sup> *Brookhaven National Laboratory, Upton, New York 11973, USA*  
<sup>74</sup> *Langston University, Langston, Oklahoma 73050, USA*  
<sup>75</sup> *University of Oklahoma, Norman, Oklahoma 73019, USA*  
<sup>76</sup> *Oklahoma State University, Stillwater, Oklahoma 74078, USA*  
<sup>77</sup> *Brown University, Providence, Rhode Island 02912, USA*  
<sup>78</sup> *University of Texas, Arlington, Texas 76019, USA*  
<sup>79</sup> *Southern Methodist University, Dallas, Texas 75275, USA*  
<sup>80</sup> *Rice University, Houston, Texas 77005, USA*  
<sup>81</sup> *University of Virginia, Charlottesville, Virginia 22901, USA and*  
<sup>82</sup> *University of Washington, Seattle, Washington 98195, USA*

(Dated: August 6, 2008)

We present an observation for  $ZZ \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-$  ( $\ell, \ell' = e$  or  $\mu$ ) production in  $p\bar{p}$  collisions at a center-of-mass energy of  $\sqrt{s} = 1.96$  TeV. Using  $1.7 \text{ fb}^{-1}$  of data collected by the D0 experiment at the Fermilab Tevatron Collider, we observe three candidate events with an expected background of  $0.14^{+0.03}_{-0.02}$  events. The significance of this observation is 5.3 standard deviations. The combination of D0 results in this channel, as well as in  $ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$ , yields a significance of 5.7 standard deviations and a combined cross section of  $\sigma(ZZ) = 1.60 \pm 0.63$  (stat.) $^{+0.16}_{-0.17}$  (syst.) pb.

PACS numbers: 12.15.Ji, 07.05.Kf, 13.85.Qk, 14.70.Hp

Studies of the pair production of electroweak gauge bosons provide an interesting test of the electroweak theory predictions [1]. In contrast with other diboson processes,  $Z$  boson pair production ( $ZZ$ ) does not involve trilinear gauge boson interactions within the standard model (SM). The observation of an unexpectedly high cross section could indicate the presence of anomalous  $ZZZ$  or  $ZZ\gamma$  couplings [2]. The SM prediction for the total  $ZZ$  production cross section in  $p\bar{p}$  collisions at the Fermilab Tevatron Collider at  $\sqrt{s} = 1.96$  TeV is  $\sigma(ZZ) = 1.4 \pm 0.1$  pb [3]. The requirement of leptonic  $Z$  boson decays reduces the observable cross section, making its measurement rather challenging. The accumulation of integrated luminosities in excess of  $3 \text{ fb}^{-1}$  at the Fermilab Tevatron Collider and the development of highly optimized event selection criteria has now made possible the direct observation of  $ZZ$  production.

Previous investigations of  $ZZ$  production have been performed both at the Fermilab Tevatron  $p\bar{p}$  and the CERN  $e^+e^-$  (LEP) [4] Colliders. The D0 collaboration reported a search for  $ZZ \rightarrow \ell^+\ell^-\ell'^+\ell'^-$  ( $\ell, \ell' = e$  or  $\mu$ ) with  $1 \text{ fb}^{-1}$  of data that provided a 95% C.L. limit of  $\sigma(ZZ) < 4.4$  pb [5]. The CDF collaboration reported a signal for  $ZZ$  production with a significance of 4.4 standard deviations from combined  $ZZ \rightarrow \ell^+\ell^-\ell'^+\ell'^-$  and  $ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$  searches, and measured a production cross section of  $\sigma(ZZ) = 1.4^{+0.7}_{-0.6}$  pb [6].

In this Letter, we present a search for  $Z$  boson pairs where the  $Z$  bosons have decayed to either electron or muon pairs, resulting in final states consisting of four electrons ( $4e$ ), four muons ( $4\mu$ ) or two muons and two electrons ( $2\mu 2e$ ). Data used in this analysis were collected with the D0 detector at the Fermilab Tevatron  $p\bar{p}$  Collider at  $\sqrt{s} = 1.96$  TeV between June 2006 and May 2008. The integrated luminosities [7] for the three analyzed channels are about  $1.7 \text{ fb}^{-1}$ . This result is later combined with that from an earlier similar analysis [5] using data collected from October 2002 to February 2006 and corresponding to an integrated luminosity of  $1 \text{ fb}^{-1}$ .

The D0 detector [8] consists of a central tracking system, comprised of a silicon microstrip tracker (SMT), and a central fiber tracker (CFT), providing coverage to pseudorapidity  $|\eta| < 3$  [9], both located within a 2 T superconducting solenoidal magnet. Three liquid argon and uranium calorimeters provide coverage to  $|\eta| < 4$ . Electromagnetic objects are well reconstructed in the regions of the central calorimeter (CC) with coverage to  $|\eta| < 1.1$  and the end calorimeters (EC) with coverage of  $1.5 < |\eta| < 3.2$ . A muon system surrounds the calorimetry, consisting of three layers of scintillators and drift tubes and 1.8 T iron toroids, with a coverage of  $|\eta| < 2$ .

This analysis employs a combination of single and dielectron triggers for the  $4e$  channel. Similarly, single and dimuon triggers are used for the  $4\mu$  channel. The  $2\mu 2e$  channel uses a combination of all these triggers, and additional specific electron-muon triggers. The triggering

efficiency for events with four leptons having high transverse momentum ( $p_T$ ) that satisfy all offline selection requirements exceeds 99%.

For the  $4e$  channel, we require four electrons with ordered transverse energies  $E_T > 30, 25, 15$ , and  $15$  GeV, respectively. Electrons must be reconstructed either in the CC region or in the EC region, and be isolated from other energy clusters in the calorimeter. Electrons in the CC are required to satisfy identification criteria based on a multivariate discriminant derived from calorimeter shower shape and a matched track reconstructed in the SMT and CFT. Electrons in the EC are not required to have a matched track, but must satisfy more stringent shower shape requirements. At least two electrons must be in the CC region. With no requirement applied on the charge of the electrons at this stage to increase selection efficiency, three possible  $ZZ$  combinations can be formed for each  $4e$  event. Events are required to have a solution for which one  $ee$  combination has an invariant mass  $> 70$  GeV and the other  $> 50$  GeV. Finally, events are split into three categories, depending on the number of electrons in the CC region. Subsamples with two electrons, with three electrons and with four or more electrons in the CC are denoted as  $4e_{2C}$ ,  $4e_{3C}$ , and  $4e_{4C}$ , respectively. The three exclusive subsamples contain significantly different levels of background contamination and thus the separation of the subsamples provides more sensitivity to the search.

For the  $4\mu$  channel, each muon must satisfy quality criteria based on scintillator and wire chamber information from the muon system, and have a matched track in the central tracker. We require that the four most energetic muons have ordered transverse momenta  $p_T > 30, 25, 15$ , and  $15$  GeV, respectively. At least three muons in the event must be isolated, each passing a requirement of less than 2.5 GeV of transverse energy deposited in the calorimeter in the annulus  $0.1 < \Delta R < 0.4$  centered around the muon track [10]. Finally, the muon is required to be well reconstructed and to originate from the primary event vertex. Of the three possible  $ZZ$  combinations per event that can be formed without considering muon charge at this stage, a solution is required where one  $\mu\mu$  combination has an invariant mass  $> 70$  GeV and the other  $> 50$  GeV.

For the  $2\mu 2e$  channel, the two most energetic electrons and muons in an event must have  $E_T(p_T) > 25, 15$  GeV. All muons and electrons must satisfy the single lepton selection criteria defined for the  $4e$  and  $4\mu$  final states. In addition, electrons and muons are required to be spatially separated by  $\Delta R > 0.2$  to remove  $Z \rightarrow \mu\mu$  background with muons radiating photons giving events with two muon and two trackless electron candidates. At least one muon must satisfy the same calorimeter isolation requirement imposed in the  $4\mu$  final state. A solution is required where one pair of same flavor leptons has an invariant mass  $> 70$  GeV, and the other  $> 50$  GeV. Fi-

nally, events are split into three categories depending on the number of electrons in the CC region. Subsamples with no electron, with one electron and with two or more electrons in the CC are denoted as  $2\mu 2e_{0C}$ ,  $2\mu 2e_{1C}$  and  $2\mu 2e_{2C}$ , respectively. As in the  $4e$  channel, these subsamples have significantly different levels of background contamination.

A Monte Carlo (MC) simulation is used to determine the expected number of signal events in each subchannel. The small contribution from  $ZZ$  events with at least one  $Z$  boson decaying into tau pairs is also included in the signal. Simulated events are generated using PYTHIA [11] and passed through a detailed GEANT-based simulation [12] of the detector response. Differences between MC simulation and data in the reconstruction and identification efficiencies for electrons and muons are corrected using efficiencies derived from large data samples of inclusive  $Z \rightarrow \ell\ell$  ( $\ell = e$ , or  $\mu$ ) events. The systematic uncertainty in the signal is dominated by the uncertainty in the theoretical cross section (6.25%), the uncertainty on the lepton identification and reconstruction efficiencies ( $\approx 4\%$  for the  $4e$  and  $4\mu$  subchannels and  $\approx 2.5\%$  for the  $2\mu 2e$  subchannels) and a 6.1% uncertainty on the luminosity measurement [7]. Additional smaller sources of systematic uncertainty arise from energy and momentum resolutions and MC modeling of the signal process.

Backgrounds to the  $ZZ$  signal originate from top quark pair ( $t\bar{t}$ ) production and from events with  $W$  and/or  $Z$  bosons that decay to leptons and additional jets or photons. The jets can then be misidentified as leptons or contain true electrons or muons from in-flight decays of pions, kaons, or heavy-flavored hadrons.

The background from  $t\bar{t}$  production is estimated from MC, assuming the cross section of  $\sigma(t\bar{t}) = 7.9$  pb [13] for a top quark mass of 170 GeV. The systematic uncertainty includes a 10% uncertainty on  $\sigma(t\bar{t})$ , as well as contributions from the variation in cross section and acceptance originating from uncertainties on the mass of the top quark.

To estimate the misidentified lepton background, we first measure the probability for a jet to produce an electron or muon that satisfy the identification criteria from data using a “tag and probe” method [5]. The probability for a jet to mimic an electron, parameterized in terms of jet  $E_T$  and  $\eta$ , is equal to  $4 \times 10^{-4}$  for the case of CC electrons with a matched track and  $5 \times 10^{-3}$  in the case of EC electrons for which no track matching is applied. The probability for a 15 GeV (100 GeV) jet to produce a muon of  $p_T > 15$  GeV is  $10^{-4}$  ( $10^{-2}$ ) without requiring muon isolation, and it is  $10^{-5}$  ( $10^{-4}$ ) when the muon is required to be isolated. A systematic uncertainty of 30% on the jet-to-lepton misidentification probabilities is estimated by varying the selection criteria of the control samples used.

The probabilities for jets to be misidentified as elec-

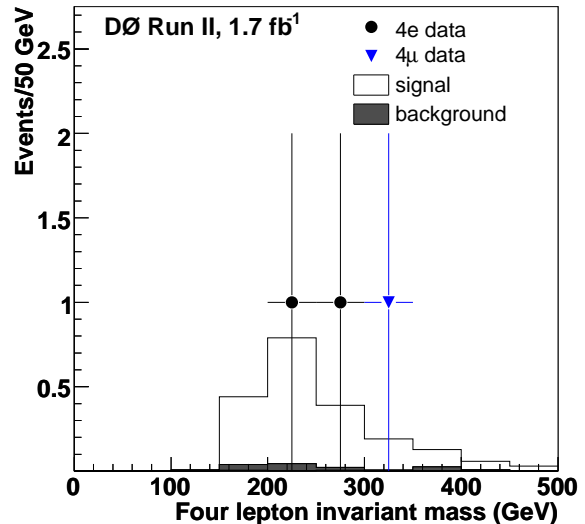


FIG. 1: Distribution of four lepton invariant mass in data, expected signal, and expected background.

trons are then applied to jets in  $eee$ +jets and  $\mu\mu e$ +jets data to determine the background to the  $4e$  and  $2\mu 2e$  channels, respectively. This method takes into account contributions from  $Z$ +jets,  $Z$ + $\gamma$ +jets,  $WZ$ +jets,  $WW$ +jets,  $W$ +jets, and events with  $\geq 4$  jets. However, this method double counts the contribution from  $Z$ +jets. A correction is measured, amounting to  $\approx 20\%$ , to correct for the double counting. The probabilities for jets to contain a muon are applied to jets in  $\mu\mu$ +jets data to determine a background estimate for the  $4\mu$  channel. Systematic uncertainties on this background arise from the 30% uncertainty in measured misidentification rates, and from the limited statistics of the data remaining in the samples after selection.

Table I summarizes the expected signal and background contributions to each subchannel, as well as the number of candidate events in data. The total signal and background expectations are  $1.89 \pm 0.08$  events and  $0.14^{+0.03}_{-0.02}$  events, respectively. We observe a total of three candidate events in the data, two in the  $4e_{4C}$  subchannel and one in the  $4\mu$  subchannel. Table II summarizes some of their kinematic characteristics. The quoted dilepton masses in the table correspond to the one out of the three possible combinations having opposite charge within the pairs and having a dilepton mass closest to that of the  $Z$  boson. Figure 1 shows the distribution of the four lepton invariant mass for data and for the expected signal and background.

We extract the significance of the observed event distributions using a negative log-likelihood ratio (LLR) test-statistic [14]. As input, we use the expected yields (number of events) from signal and background, separated into the seven subchannels compared to the ob-

TABLE I: The integrated luminosity, expected number of signal ( $Z/\gamma^* Z/\gamma^*$ ) and background events ( $t\bar{t}$  and  $Z(\gamma)$ +jets which includes all  $W/Z/\gamma$ +jets contributions), and the number of observed candidates in the seven  $ZZ \rightarrow \ell^+\ell^-\ell'^+\ell'^-$  subchannels. Uncertainties reflect statistical and systematic contributions added in quadrature.

Subchannel	$4e_{2C}$	$4e_{3C}$	$4e_{4C}$	$4\mu$	$2\mu 2e_{0C}$	$2\mu 2e_{1C}$	$2\mu 2e_{2C}$
Luminosity ( $\text{fb}^{-1}$ )	$1.75 \pm 0.11$	$1.75 \pm 0.11$	$1.75 \pm 0.11$	$1.68 \pm 0.10$	$1.68 \pm 0.10$	$1.68 \pm 0.10$	$1.68 \pm 0.10$
Signal	$0.084 \pm 0.008$	$0.173 \pm 0.015$	$0.140 \pm 0.012$	$0.534 \pm 0.043$	$0.058^{+0.007}_{-0.006}$	$0.352 \pm 0.040$	$0.553^{+0.045}_{-0.044}$
$Z(\gamma)$ +jets	$0.030^{+0.009}_{-0.008}$	$0.018^{+0.008}_{-0.007}$	$0.002^{+0.002}_{-0.001}$	$0.0003 \pm 0.0001$	$0.03^{+0.02}_{-0.01}$	$0.05 \pm 0.01$	$0.008^{+0.004}_{-0.003}$
$t\bar{t}$	–	–	–	–	$0.0012^{+0.0016}_{-0.0009}$	$0.005 \pm 0.002$	$0.0007^{+0.0009}_{-0.0005}$
Observed events	0	0	2	1	0	0	0

TABLE II: Characteristics of the observed candidate events.  $\eta$  and  $\phi$  values are measured relative to the location of the  $p\bar{p}$  collision.  $M_{\ell\ell}$  is the mass of the lepton pair.

4e candidate 1		$e_1^+$	$e_2^+$	$e_3^-$	$e_4^-$
	$p_T$ (GeV)	107	59	52	16
	$\eta$	0.66	0.25	-0.64	-0.85
	$\phi$	4.10	1.08	0.46	2.62
	$M_{\ell\ell}$ (GeV)	$e_1^+ e_4^-$ $89 \pm 3$		$e_2^+ e_3^-$ $61 \pm 2$	
4e candidate 2		$e_1^+$	$e_2^+$	$e_3^-$	$e_4^-$
	$p_T$ (GeV)	83	75	35	26
	$\eta$	0.64	0.40	0.85	1.17
	$\phi$	6.16	3.80	3.83	1.40
	$M_{\ell\ell}$ (GeV)	$e_1^+ e_3^-$ $99 \pm 3$		$e_2^+ e_4^-$ $90 \pm 4$	
4 $\mu$ candidate		$\mu_1^+$	$\mu_2^-$	$\mu_3^-$	$\mu_4^+$
	$p_T$ (GeV)	115	77	42	24
	$\eta$	0.04	-1.01	0.77	-1.93
	$\phi$	1.69	4.26	5.29	0.36
	$M_{\ell\ell}$ (GeV)	$\mu_1^+ \mu_3^-$ $148^{+32}_{-18}$		$\mu_2^- \mu_4^+$ $90^{+12}_{-8}$	

served yields. The modified frequentist method returns the probability ( $p$ -value) of the background-only fluctuating to give the observed yields or higher. In  $5 \times 10^9$  background pseudo-experiments, we find 213 trials with an LLR value smaller or equal to that observed in data. This gives a  $p$ -value of  $4.3 \times 10^{-8}$  which corresponds to a 5.3 standard deviation ( $\sigma$ ) observed significance ( $3.7\sigma$  expected). The probability for the signal plus background hypothesis to give less signal-like observations than the observed one is 0.87. A correction factor of 0.93, derived using PYTHIA, is used to convert the measured cross section for  $(Z/\gamma^*)(Z/\gamma^*)$  into that for  $ZZ$  production. Minimizing the LLR function we obtain a cross section of  $\sigma(ZZ) = 1.75^{+1.27}_{-0.86}$  (stat.)  $\pm 0.13$  (syst.) pb for this analysis.

This result is combined with the results from an independent  $ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$  search [15], and the previous  $(Z/\gamma^*)(Z/\gamma^*) \rightarrow \ell^+\ell^-\ell'^+\ell'^-$  analysis [5] which used a separate data sample with a looser mass requirement

$M(\ell\ell) > 30$  GeV. The earlier search contributes no signal events and we have scaled its background estimate to the tighter kinematic range used in the recent analysis. The combination of the three analyses is performed taking into account the correlations of systematic uncertainties between subchannels and among analyses. The resulting  $p$ -value is  $6.2 \times 10^{-9}$ , and the significance for observation of  $ZZ$  production increases to  $5.7\sigma$  ( $4.8\sigma$  expected). The probability for the signal plus background hypothesis to give less signal-like observations than the observed one is 0.71. We therefore report the observation of a  $ZZ$  signal at a hadron collider with a combined cross section of  $\sigma(ZZ) = 1.60 \pm 0.63$  (stat.) $^{+0.16}_{-0.17}$  (syst.) pb, consistent with the standard model expectation.

We thank the staffs at Fermilab and collaborating institutions, and acknowledge support from the DOE and NSF (USA); CEA and CNRS/IN2P3 (France); FASI, Rosatom and RFBR (Russia); CNPq, FAPERJ, FAPESP and FUNDUNESP (Brazil); DAE and DST (India); Colciencias (Colombia); CONACyT (Mexico); KRF and KOSEF (Korea); CONICET and UBACyT (Argentina); FOM (The Netherlands); STFC (United Kingdom); MSMT and GACR (Czech Republic); CRC Program, CFI, NSERC and WestGrid Project (Canada); BMBF and DFG (Germany); SFI (Ireland); The Swedish Research Council (Sweden); CAS and CNSF (China); Alexander von Humboldt Foundation (Germany); and the Istituto Nazionale di Fisica Nucleare (Italy).

- 
- [a] Visitor from Augustana College, Sioux Falls, SD, USA.
  - [b] Visitor from The University of Liverpool, Liverpool, UK.
  - [c] Visitor from INFN Torino, Torino, Italy.
  - [d] Visitor from ECFM, Universidad Autonoma de Sinaloa, Culiacán, Mexico.
  - [e] Visitor from II. Physikalisches Institut, Georg-August-University, Göttingen, Germany.
  - [f] Visitor from Helsinki Institute of Physics, Helsinki, Finland.
  - [g] Visitor from Universität Bern, Bern, Switzerland.
  - [h] Visitor from Universität Zürich, Zürich, Switzerland.
  - [†] Deceased.

- [1] R.W. Brown and K.O. Mikaelian, Phys. Rev. D **19**, 922 (1979).
- [2] U. Baur and D. Rainwater, Phys. Rev. D **62**, 113011 (2000).
- [3] J. M. Campbell and R. K. Ellis, Phys. Rev. D **60**, 113006 (1999).
- [4] R. Barate *et al.* [ALEPH Collaboration], Phys. Lett. B **469**, 287 (1999); J. Abdallah *et al.* [DELPHI Collaboration], Eur. Phys. J. C **30**, 447 (2003); M. Acciarri *et al.* [L3 Collaboration], Phys. Lett. B **465**, 363 (1999); G. Abbiendi *et al.* [OPAL Collaboration], Eur. Phys. J. C **32**, 303 (2003).
- [5] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **100**, 131801 (2008).
- [6] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **100**, 201801 (2008).
- [7] T. Andeen *et al.* , FERMILAB-TM-2365 (2007).
- [8] V. M. Abazov *et al.* [D0 Collaboration], Nucl. Instrum. Meth. Phys. Res. A **565**, 463 (2006).
- [9] The D0 coordinate system is cylindrical with the  $z$ -axis along the proton beamline and the polar and azimuthal angles denoted as  $\theta$  and  $\phi$  respectively. The pseudorapidity is defined as  $\eta = -\ln[\tan(\theta/2)]$ .
- [10] The variable  $\Delta R$  between two objects  $i$  and  $j$  is defined as  $\Delta R = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}$ .
- [11] T. Sjöstrand *et al.*, Comput. Phys. Commun. **135**, 238 (2001).
- [12] R. Brun and F. Carminati, CERN Program Library Long Writeup W5013, 1993 (unpublished).
- [13] N. Kidonakis and R. Vogt, Phys. Rev. D **68**, 114014 (2003).
- [14] W. Fisher, FERMILAB-TM-2386-E (2007).
- [15] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. D **78**, 072002 (2008).